

Do Anomalous Narrow Line Quasars Cast Doubt on Virial Mass Estimation?

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ABSTRACT

Anomalous Narrow-Line Quasars (ANLs) are a population of quasars with narrow $H\beta$, and sometimes $[OIII]$ broader than ~ 1000 km/s, in total comprising $\sim 10 - 30\%$ (most likely $\sim 25\%$) of Type I quasars at $0.2 < z < 0.8$. We find that virial masses using the $H\beta$ and $MgII$ lines systematically differ for ANLs by an average of as much as 0.5 dex. Because the broad $H\beta$ component width increases in ANLs but $MgII$ does not, we might suspect $H\beta$ -based virial masses for ANLs are wrong but $MgII$ masses are correct. If this is due to an outflow reaching the lower-ionization potential $H\beta$ line, CIV masses will be similarly flawed. However, we cannot be certain of this explanation without followup work, and may be unable to identify which quasars are ANLs at $z > 0.8$. Therefore, it is essential that ANLs be well-understood and well-modeled in order to allow the use of virial mass estimators on large optical spectroscopic catalogs, particularly at $z < 0.4$ and $z > 2.0$ where only one broad line is available for use in mass estimation.

Key words: black hole physics — galaxies: evolution — galaxies: nuclei — quasars: general — accretion, accretion disks

1 INTRODUCTION

The quasar “broad-line region” (BLR) from which high-velocity gas produces correspondingly broad spectral emission lines, with typical FWHM in the 2000-20000 km/s range. Prominent emission lines visible in optical spectra at $z > 0.5$ include, from ionization potential placing them nearest to the central black hole, CIV, a broad component of $H\beta$, and $MgII$.

For some individual active galactic nuclei, reverberation mapping (Peterson et al. 2004; Bentz et al. 2009) has been able to confirm the locations of broad emission lines. In a time series of spectra for the same object, an increase in the continuum luminosity is followed, often hundreds of days later, by a similar flare in CIV and then $H\beta$. Assuming the flare propagates outward at the speed of light, the delay can be used to infer a radius to BLR spectral lines. It is hoped that broad-line region velocities are predominantly virial. For reverberation-mapped quasars, this approximation combined with Kepler’s Laws then allows the use of CIV and $H\beta$ to infer a black hole mass.

An empirical relationship between the reverberation radii and the continuum flux allows ‘virial mass estimators’ (McLure & Jarvis 2002; McLure & Dunlop 2004; Vestergaard & Peterson 2006; Wang et al. 2009; Onken & Kollmeier 2008; Risaliti et al. 2009; Rafiee & Hall 2010) that can be used on just one spectrum rather than

a time series. Mass estimates have allowed a dramatic improvement in our understanding of distant quasars in several ways, including the tight $M - \sigma$ correlation between black hole mass and stellar dispersion in the host galactic bulge (Ferrarese & Merritt 2000; Gebhardt et al. 2000), analysis of the quasar mass distribution as a function of redshift (Vestergaard et al. 2008), and analysis of the quasar mass-luminosity plane (Steinhardt & Elvis 2010a, 2011). The last two of these entirely depend upon virial mass estimates, while the others would require virial mass estimates if considered at higher redshift.

However, CIV in particular may also be substantially broadened by radiation pressure and quasar outflows (Marconi et al. 2009). If so, this extra velocity would result in an overestimate of the mass of the central black hole. It has recently been reported that $\sim 25\%$ of quasars at $0.2 < z < 0.8$ have anomalous narrow lines, and that these ANL quasars are associated with broadened $H\beta$ but not broadened $MgII$. In this paper, we consider the implications of this broadening on virial mass estimation.

In § 2, we describe our line-fitting for the $H\beta/[OIII]$ complex and identification of ANLs. We also examine the response of other emission lines to an increased narrow $H\beta$ width. The resulting response of virial mass estimates in ANLs is examined in § 3. Finally, the possible implications of these objects upon the validity of virial mass estimation are discussed in § 4.

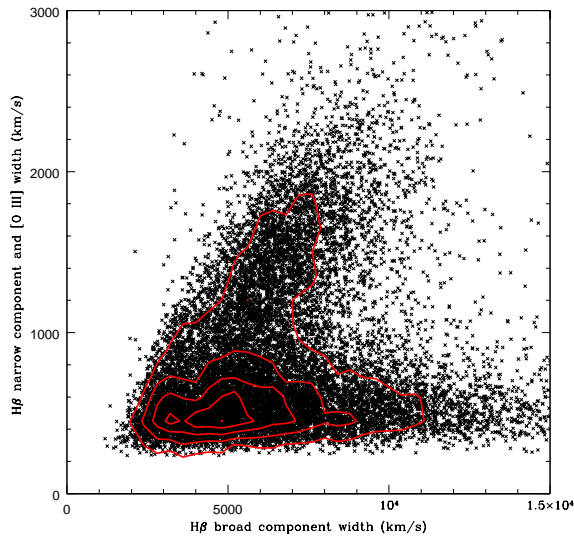


Figure 1. Comparison of the [OIII] FWHM and $H\beta$ broad-component FWHM for quasars in the SDSS DR7 catalog. Lower narrow-line velocities are accompanied by a wide range of $H\beta$ widths, but anomalous narrow lines are well-correlated with broad $H\beta$, increasing with increasing broad $H\beta$ width.

2 QUASARS WITH BROAD $H\beta$ LINES

We investigate the properties of the $H\beta$ and [OIII] lines, as in Steinhardt & Silverman (2011), with a fitting prescription similar to Shen et al. (2008). First, the catalog redshift is assumed and the continuum is fit at rest wavelengths [4435, 4700] and [5100, 5535] Å. The continuum is best-fit as a power law combined with a Fe template from Bruhweiler & Verner (2008), where the Fe template has two free parameters: (1) an amplitude and (2) convolution with a Gaussian of variable width. Once the continuum and iron lines are removed, $H\beta$ line is fit with two Gaussians and the [OIII] doublet with a pair of Gaussians, such that the [OIII] doublet is constrained to have the 3:1 amplitude ratio physically required by the fine structure transitions involved and the two [OIII] widths are required to be identical to the width of the $H\beta$ narrow component.

A comparison between the $H\beta$ broad-line FWHM and combined narrow $H\beta$ and [OIII] FWHM shows two populations (Fig. 1, a population with standard narrow lines uncorrelated with the $H\beta$ broad-line width and a population with broader “narrow” lines well correlated with the broad $H\beta$ component. The key question for virial mass estimation, then, is whether this broader $H\beta$ is due to an increased virial velocity or comes from non-virial broadening. We divide the SDSS DR7 sample by narrow-line width, as in Table 2. We then co-add spectra within each bin to examine the dependence of MgII emission on narrow $H\beta$ width. Changes in other emission lines and the spectral continuum of ANLs are discussed in Steinhardt & Silverman (2011) but are beyond the scope of this paper.

Although the $H\beta$ FWHM increases in ANLs, the MgII line width (Fig. 2) does not increase. Since MgII has an ionization potential placing it at a larger radius from the central black hole (Peterson 2008), one possible explanation

Table 1. Properties of quasars in the SDSS DR7 catalog binned by narrow-line width

σ (km/s)	FWHM (km/s)	Color	N	Fraction	$\log L_{bol}$ (erg/s)
100–200	235–471	Black	3549	0.217	45.41
200–300	471–706	Black	4941	0.303	45.51
300–400	706–942	Red	2309	0.141	45.61
400–500	942–1177	Red	1366	0.084	45.68
500–600	1177–1413	Yellow	1086	0.067	45.72
600–700	1413–1648	Green	1018	0.062	45.82
700–800	1648–1884	Cyan	743	0.045	45.90
800–900	1884–2119	Blue	424	0.026	46.00
900–1000	2119–2355	Magenta	227	0.014	46.01

might be an outflow propagating only partway through the broad-line region.

It is also important to determine whether other narrow lines might be good indicators of ANLs, since [OIII] is only visible at $0.2 \lesssim z \lesssim 0.8$. For a the small fraction of our sample lying at $z < 0.39$, the [SII] $\lambda 6717, 6730$ doublet is visible. In standard quasars, [SII] is a pair of narrow lines, like [OIII] and the narrow component of $H\beta$. Although very few objects are included at high [OIII] widths, it does appear that the [SII] amplitude may be decreasing with increased narrow-line width, while the [SII] width remains fixed (Fig. 2). Still, [SII] appears to be a poor indicator of whether a quasar is an ANL.

However, [NeV] $\lambda 3426$ may be a better indicator, as it broadens with broader “narrow” lines (Fig. 2). As in Steinhardt & Silverman (2011), approximately 11% of quasars are well-measured with broad [OIII] and a broadened $H\beta$ narrow component, with an additional $\sim 15\%$ showing anomalous narrow lines where $H\beta$ and [OIII] are poorly matched, most commonly with more broadening found in $H\beta$ than in [OIII]. Thus, although [OIII] and [NeV] may turn out to be equally good indicators of ANLs, they are likely not good enough to identify the full set. It may, however, be that finding these two forbidden lines broadened together, while non-forbidden lines and one other forbidden line are not, is useful in developing a physical model for ANLs.

3 ANLS AND VIRIAL MASS ESTIMATION

One of the possible explanations for broader narrow $H\beta$ and [OIII], correlated with a broad $H\beta$ component, is a strong outflow broadening all three lines. Such an outflow would result in substantial non-virial motion in the $H\beta$ broad component. Recent work using large catalogs to investigate the properties of quasar accretion has been greatly enhanced by virial mass indicators (McLure & Jarvis 2002; McLure & Dunlop 2004; Vestergaard & Peterson 2006), predicated amongst other assumptions upon the idea that the gas producing $H\beta$ ’s broad component is virialized. This assumption has been questioned in more recent work (Wang et al. 2009; Rafiee & Hall 2010), in which the virial velocity for broad lines is fit as $v^2 = \text{FWHM}^2$ rather than $v^2 = \text{FWHM}^2$. Rafiee & Hall (2010) use various statistical methods to find for MgII a series of best-fit values

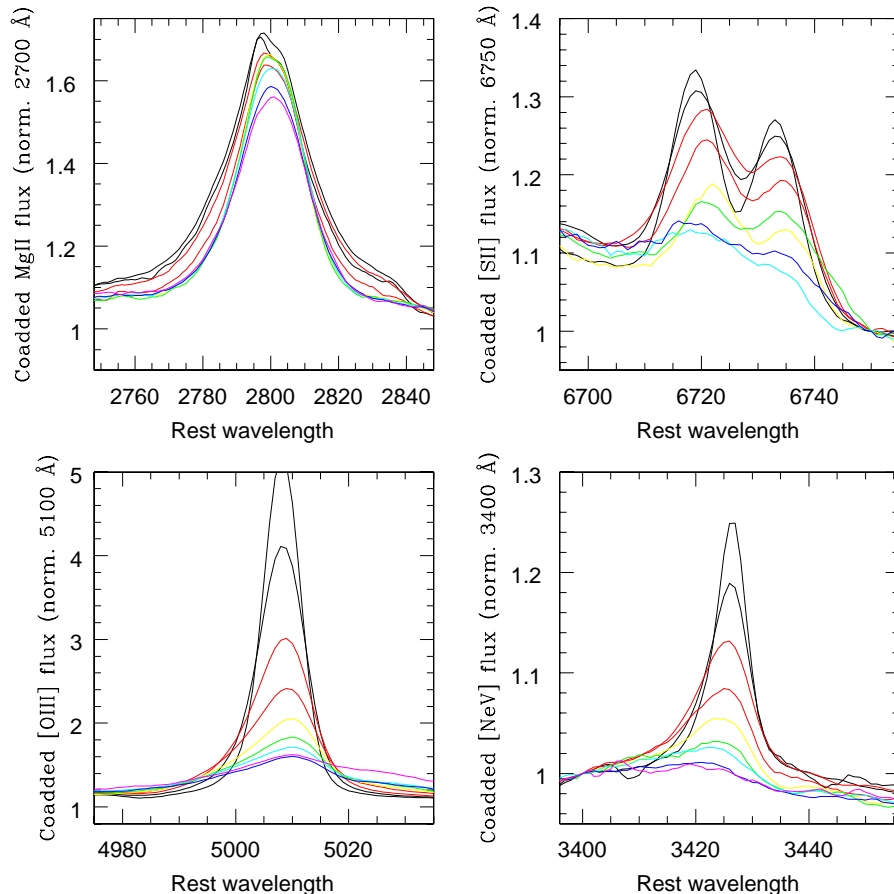


Figure 2. Comparison of co-added quasar spectra near the MgII (top left), [SII] (top right), [OIII] (bottom left), and [NeV] (bottom right) emission lines at different narrow-line widths binned and colored as in Table 2. At each wavelength, only spectra at redshifts where those wavelengths can be measured were co-added. For [SII], there are too few objects at low z to produce a magenta curve.

$1.21 < \gamma < 3.95$, arguing that the best of these techniques is the one yielding $\gamma = 1.21 \pm 0.40$, within 2σ of $\gamma = 2$.

A strong outflow would produce additional broadening of $H\beta$, and thus $\gamma < 2$. Broader narrow lines are not, however, correlated with broadening in MgII (Fig. 2). MgII and $H\beta$ masses show no offset, with a scatter of 0.22 dex (Shen et al. 2008). Thus, if MgII remains virial, a comparison between MgII-based virial masses and $H\beta$ -based virial masses is a potential test for the nature of $H\beta$ broadening. Systematically larger $H\beta$ masses in ANL systems would then indicate that $H\beta$ is due to non-virial motion such as an outflow, while continued agreement would indicate that $H\beta$ remains virial, perhaps broadened because ANL systems produce the proper ionization potential for $H\beta$ at a different radius.

The Shen et al. (2011) catalog produces MgII-based virial masses using the prescription of McLure & Dunlop (2004) (along other estimators), which has been previously shown to agree with $H\beta$ masses to within a scatter of ~ 0.22 dex (Shen et al. 2008). However, these catalogs restrict not just [OIII] but also the narrow component of $H\beta$ to ≤ 1200 km/s in FWHM. ANLs include a broader $H\beta$ narrow com-

ponent, so restricting the FWHM to 1200 km/s will also underestimate the $H\beta$ narrow component width.

As a result, the line flux assumed by the fit to represent the $H\beta$ broad component would actually have been a combination of the broad component and the wings of the narrow component, resulting in a broad component fit that was artificially too narrow. An underestimate of the $H\beta$ FWHM will result in an underestimate in the virial mass $M_{BH} \propto \text{FWHM}^2$.

Using the fitting routine described in § 2, we produce an alternative set of masses from the broad $H\beta$ component, where the narrow component is no longer constrained to lie at a FWHM less than 1200 km/s. For narrow [OIII] lines, there is good agreement between both sets of $H\beta$ masses, but for ANLs, the Shen et al. (2011) masses are systematically lower (Fig. 3). This is likely due to the effect described above, where a Shen et al. (2011) fit a combination of the broad and narrow component as their broad component. Objects are only included in this sample if they have high enough signal-to-noise for our routine to produce a high-quality fit. Note that the high signal-to-noise sample contains a larger ANL fraction than the overall sample, since ANLs are on average more luminous than other quasars.

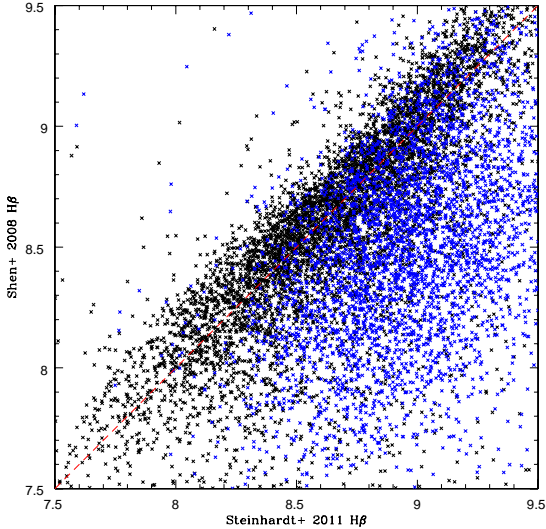


Figure 3. Comparison of $H\beta$ masses between Shen et al. 2011, where the FWHM of [OIII] and narrow $H\beta$ is constrained to be narrower than 1200 km/s, and masses produced in this paper, where these narrow lines are unconstrained. The sample consists of 10133 well-measured quasars at $0.4 < z < 0.8$. Black points are objects with [OIII] narrower than 1200 km/s, while blue points correspond to objects with broader narrow components.

Table 2. Mean virial mass comparison between this work and Shen11 for well-measured quasars binned by [OIII] width, $0.5 < z < 0.6$

FWHM (km/s)	$\log M/M_\odot$ ($H\beta$, SS11)	$\log M/M_\odot$ (MgII, Shen11)	$\log M/M_\odot$ ($H\beta$, Shen11)
235–471	8.52	8.35	8.49
471–706	8.63	8.48	8.61
706–942	8.63	8.46	8.53
942–1177	8.61	8.44	8.44
1177–1413	8.67	8.37	8.30
1413–1648	8.75	8.40	8.32
1648–1884	8.83	8.44	8.35
1884–2119	8.92	8.51	8.40
2119–2355	9.02	8.53	8.46

For 4716 high signal-to-noise ANLs at $0.4 < z < 0.8$ (where both $H\beta$ and MgII masses are available), our $H\beta$ masses average 0.474 dex higher than Shen et al. (2011) using $H\beta$, while for 5417 other quasars our masses average 0.075 dex higher. Some of this discrepancy is due to changes in the FeII template used and other line-fitting details, which are particularly important for MgII. Compared to the Shen et al. (2011) MgII masses, our masses average 0.455 dex higher for ANLs and 0.170 dex higher for other quasars. Since the mass and luminosity distributions change with redshift (Steinhardt & Elvis 2010a), it is likely best to compare these mass estimates in a relatively narrow redshift range, yet one wide enough to include a large enough sample to draw meaningful conclusions. At $0.5 < z < 0.6$ (Table 3), our $H\beta$ masses (Vestergaard & Peterson 2006)

average 0.047 dex higher than (Shen et al. 2011) for 1161 “standard” quasars ($\text{FWHM} < 1000$ km/s), but 0.393 dex higher for 661 ANLs (> 1000 km/s). More generally, the discrepancy between our unconstrained $H\beta$ masses and the Shen et al. (2008) MgII masses, which are based upon a line that does not change in ANLs compared to other objects, grows with increasing [OIII] width (Table 3).

For comparison, $H\beta$ and MgII virial masses in the Shen et al. (2008) catalog show good agreement for all quasars. If the uncertainty in comparing $H\beta$ and MgII masses is uncorrelated between different quasars with a scatter of ~ 0.22 dex (Shen et al. 2008), the systematic error produced by restricting the narrow $H\beta$ component to 1200 km/s would be the dominant source of error in ANL masses.

Alternative estimates for the statistical uncertainty in $H\beta$ alone include 0.4 dex (Vestergaard & Peterson 2006) and 0.21 dex (Steinhardt & Elvis 2010b), with the latter in addition to 0.15 dex scatter in MgII. Neither of these estimates investigated whether errors in $H\beta$ and MgII masses are correlated, as they will be for errors emanating from the empirical relationship between monochromatic continuum luminosity and inferred radius to the broad-line region. Even if the uncertainty were 0.4 dex and entirely statistical, the discrepancy between $H\beta$ and MgII mass estimates for ANLs would be at least comparable. Thus, this systematic disagreement cannot be neglected for individual objects, let alone in the analysis of large catalogs where the sample size allows a substantial reduction in the statistical error.

We also note that the Shen et al. (2011) masses show much better agreement between $H\beta$ MgII for ANLs, despite requiring as part of the fitting routine that the narrow component of $H\beta$ along with the [OIII] doublet have $\text{FWHM} \leq 1200$ km/s. As above, an artificially-low broad $H\beta$ width will produce an artificially low virial mass $M_{\text{vir}} \propto \text{FWHM}^2$. Remarkably, this lower $H\beta$ mass turns out to be empirically almost exactly the amount needed to bring $H\beta$ and MgII back into agreement: Shen et al. (2011) $H\beta$ masses average 0.094 dex higher for 5417 well-measured “standard” quasars ($\text{FWHM} < 1000$ km/s), but 0.075 dex lower for 4716 well-measured ANLs (> 1000 km/s). Similarly, at $0.5 < z < 0.6$, Shen et al. (2011) $H\beta$ masses average 0.111 dex higher for 1161 “standard” quasars ($\text{FWHM} < 1000$ km/s), but 0.065 dex lower for 661 ANLs (> 1000 km/s). It should be noted that although $H\beta$ and MgII masses appear close to agreement for both standard and ANL quasars, the typical offset has changed by ~ 0.17 dex between the two samples.

Regardless, these are not based upon the full FWHM of the $H\beta$ line. As demonstrated by Rafiee & Hall (2010), without a theoretical basis for choosing a mass estimator, different empirical calibration techniques will produce a wide variety of possible masses due to the very small number of reverberation mapping systems available. There is a theoretical basis for using the entire line FWHM and assuming virial motion in order to determine the virial component of the broad-line region velocity as $v_{\text{vir}} \propto \text{FWHM}^2$. However, this relation now seems difficult to reconcile with the existence of ANLs even for $H\beta$, let alone CIV at a smaller radius from the central black hole. It may be possible to develop a theoretical basis for reducing the measured FWHM to a purely virial FWHM if the broadening can be well-modeled. However, we currently lack that understanding, and there is no basis for using the Shen et al. (2011) prescription for

reducing the FWHM over any other that could be produced from calibrating $H\beta$ masses against $MgII$ for ANLs.

Virial mass estimation yields systematically different results for ANLs when using $H\beta$ and $MgII$, even though the effect was previously masked by constraints in the Shen et al. (2008) line fitting routine. At least one of the two must be wrong, either because of substantial non-virial motion in the broad line or because the empirical relationship between the radius to the broad-line region and continuum luminosity breaks down for ANLs. Because the $MgII$ line does not appear to change with increasing $[OIII]$ while the broad component of $H\beta$ is strongly correlated, we might suspect that the $H\beta$ masses are in error, perhaps due to a strong outflow. However, it is proper to be cautious regarding $MgII$ masses as well until there are better measurements, ideally including reverberation mapping, on ANLs and these calibrations can be examined more closely.

4 DISCUSSION

Virial mass estimates for anomalous narrow-line quasars (ANLs), a new population comprising perhaps one quarter of Type I quasars at $0.2 < z < 0.8$, appear to be flawed. For ANLs, the assumption that the line FWHM is entirely due to the virial velocity of the gas producing $H\beta$ and $MgII$ leads to a systematic disagreement in estimated mass, with the disagreement intensifying with broader $[OIII]$. We must conclude that at least one of these estimates is wrong.

The prognosis for virial mass estimation is potentially dire. The best-case scenario is likely that $H\beta$ is indeed broadened by an outflow, and we might still hope that $MgII$, which appears unresponsive to that outflow, remains virial and can be used to produce a reliable mass. Note, however, that ANLs represent $\sim 30\%$ of quasars at $0.2 < z < 0.8$. Therefore, at $0.2 < z < 0.4$, where $MgII$ does not lie within the SDSS spectrograph, 30% of quasars will have an incorrect mass. At present, that mass will be uncorrectable, although a sufficiently precise model for the outflow may allow a future correction.

It is at least fortunate that the presence of $[OIII]$ (and the narrow $H\beta$ component) around the $H\beta$ line provides an indicator for many (but not all) of the 30% of objects that will have incorrect masses. However, much of the utility of virial masses has come from our ability to take a large, statistically-complete sample (such as provided by SDSS at $z < 19.2$) and look at the mass distribution, often compared against other quasar properties. ANLs are not randomly-selected quasars, but rather quasars with specific emission line properties, continuum properties, and even host galactic properties. Even removing all ANLs from the sample and only using the remaining 70% of quasars will likely result in incorrect conclusions.

At high redshift, the problem becomes even worse. Although the BOSS (Ross et al. 2010) survey will provide a large, statistically-complete sample at high redshift, for $z > 2.0$, $MgII$ is no longer visible and CIV masses must be used. CIV has an ionization potential placing it even closer to the central black hole than $H\beta$ and is more vulnerable to effects such as radiation pressure and quasar wind (Marconi et al. 2009), and thus any outflow affecting $H\beta$ very likely will also affect CIV. So, we might expect $\geq 30\%$

of CIV masses to also be wrong due to outflows. Yet, for $H\beta$, the presence of the $[OIII]$ narrow line at least allows a detection of ANLs and confidence that non-ANLs will have better-measured masses. Although other narrow lines exist in quasar spectra, $[SII]$ is not broadened in ANLs, even though $[NeV]$ is. It is plausible that all narrow lines visible in the optical at $z > 2.0$ will remain narrow, with the strong semi-forbidden line $CIII] \lambda 1909$ perhaps our best hope for an ANL indicator. If so, not only will $\geq 30\%$ of CIV masses be overestimates, but we may also have no indication as to which masses are erroneous. Understanding ANLs well enough to model and outflows and correct for them would then become a requirement in order to make use of high-redshift quasar masses.

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REFERENCES

- Bentz M. C., Peterson B. M., Netzer H., Pogge R. W., Vestergaard M., 2009, *ApJ*, 697, 160
- Bruhweiler F., Verner E., 2008, *ApJ*, 675, 83
- Ferrarese L., Merritt D., 2000, *ApJ*, 539, L9
- Gebhardt K., Kormendy J., Ho L. C., et al., 2000, *ApJ*, 543, L5
- Marconi A., Axon D. J., Maiolino R., et al., 2009, *ApJ*, 698, L103
- McLure R. J., Dunlop J. S., 2004, *MNRAS*, 352, 1390
- McLure R. J., Jarvis M. J., 2002, *MNRAS*, 337, 109
- Onken C. A., Kollmeier J. A., 2008, *ApJ*, 689, L13
- Peterson B., 2008, *An Introduction to Active Galactic Nuclei*, Cambridge University Press: Cambridge
- Peterson B. M., Ferrarese L., Gilbert K. M., et al., 2004, *ApJ*, 613, 682
- Rafiee A., Hall P. B., 2010, *ArXiv:1011.1268*
- Risaliti G., Young M., Elvis M., 2009, *ApJ*, 700, L6
- Ross N., Sheldon E. S., Myers A. D., et al., 2010, in *Bulletin of the American Astronomical Society*, vol. 41 of *Bulletin of the American Astronomical Society*, 517
- Shen Y., Greene J. E., Strauss M. A., Richards G. T., Schneider D. P., 2008, *ApJ*, 680, 169
- Shen Y., Richards G. T., Strauss M. A., et al., 2011, *ApJS*, 194, 45
- Steinhardt C. L., Elvis M., 2010a, *MNRAS*, 402, 2637
- Steinhardt C. L., Elvis M., 2010b, *MNRAS*, 406, L1
- Steinhardt C. L., Elvis M., 2011, *MNRAS*, 410, 201
- Steinhardt C. L., Silverman J. D., 2011, *ArXiv:1109.0537*
- Vestergaard M., Fan X., Tremonti C. A., Osmer P. S., Richards G. T., 2008, *ApJ*, 674, L1
- Vestergaard M., Peterson B. M., 2006, *ApJ*, 641, 689
- Wang J., Dong X., Wang T., et al., 2009, *ApJ*, 707, 1334